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Fabrication and analysis of thin-film GaAs solar cell on flexible thermoplastic substrate using a low-pressure cold-welding

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ABSTRACT

We present flexible thin-film GaAs solar cells fabricated on thermoplastic substrates by a low-pressure cold-welding and epitaxial lift-off process. The use of polyethylene terephthalate (PET) film as a flexible substrate enables cold welding (130 °C) of gold layers between a thin-film GaAs solar cell and PET film with very low mechanical pressure (0.4 MPa), due to their thermoplastic properties. The feasibility of the proposed technique was demonstrated by fabricating GaAs single junction solar cells (without antireflection coating) on PET film, having an efficiency of 13.2%. The fabricated solar cell also showed a stable performance after 2000 cycles of bending.

1. Introduction

As the demand for flexible electronic and optoelectronic devices increases, research has being intensified to develop novel methods for fabricating thin inorganic semiconductor devices on flexible substrates [1–8]. Plastic substrates have been recently regarded as more feasible flexible substrates than other flexible alternatives due to their lower cost, light-weight, and high flexibility [9–11,38,39]. To realize the large-scale heterogeneous integration of thin inorganic semiconductor devices on other substrates such as silicon or glass, a layer transfer technique to separate the epitaxially grown inorganic semiconductor film from its parent substrate and a wafer bonding technique to bond the lifted-off inorganic semiconductor film onto a plastic substrate have been widely used for large scale applications [8,12–17]. Unfortunately, the conventional wafer bonding process is commonly conducted at high-temperature, which plastic cannot survive. This limits the application of conventional wafer bonding technology for plastic substrates. Recently, a cold-welding method, called the low-temperature wafer bonding technique, was developed to realize flexible thin-film solar cells [8]. However, the reported cold-welding method requires high mechanical pressures (i.e. 50 MPa), which can damage semiconductor devices and thereby reduce the device yield. Furthermore, a detailed optical, structural, mechanical and electrical analysis of the fabricated thin-film solar cell was seldom reported.

In order to address the abovementioned issues, in this study, we present the fabrication and detailed physical analysis of thin-film GaAs solar cell which is flexible and mechanically stable by the combination of a low-pressure cold-welding method and an epitaxial lift-off (ELO). The fabricated thin-film GaAs solar cell shows a power conversion efficiency of 13.2% under 1-sun of air mass 1.5 global (AM1.5G). The flexible GaAs thin-film solar cell also exhibits stable performance against a bending test. Detailed process procedures and material selection issues will be also discussed.

2. Experiment

Fig. 1 schematically illustrates the fabrication procedure for a flexible thin-film GaAs solar cell using the low-pressure cold-

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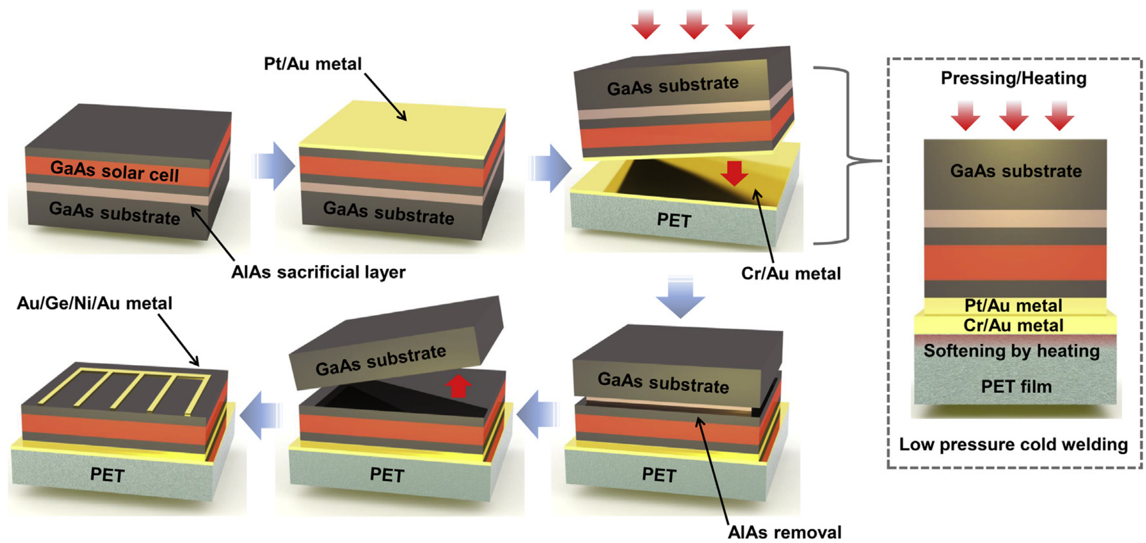

Fig. 1. Schematic illustrating the procedure for fabricating flexible GaAs solar cells via low-pressure cold-welding and epitaxial lift-off process.

welding technique. The GaAs solar cell was grown by molecular beam epitaxy (MBE) technique on a GaAs substrate covered by a 15 nm-thick AlAs sacrificial layer. In a typical GaAs solar cell structure, a p-type back-surface-field (BSF) layer and a p-type base layer are placed at the bottom, while an n-type emitter layer and an n-type window layer are placed on the top. However, the GaAs solar cell epitaxial structure for the ELO process is grown inversely, in other words, the n-type layers and p-type layers are placed at the bottom and top of the structure respectively. Si-doped n-type window layer (0.5 μm-thick GaInP), Si-doped n-type emitter layer (0.1 μm-thick GaAs), p-type base layer (2.9 μm-thick GaAs; Be-doped), and Be-doped p-type BSF layer (0.1 μm-thick GaInP) are sequentially grown from the bottom to top. All the layers grown were lattice-matched to the GaAs substrate and the GaAs solar cell epitaxy structure was sandwiched between n-/p-type GaAs contact layers. Then, the epitaxially grown GaAs solar cell was diced into pieces of 0.6 × 0.6 cm^2 and an Ohmic contact layer (Pt/Au) was formed on top of the GaAs solar cell epitaxy to enable metal–metal bonding with the metallic layer (Cr/Au) coated on the flexible carrier substrate. The carrier substrate used in this study was polyethylene terephthalate (PET) film. The Au metal coated carrier substrate and epitaxy can be kept face to face (Au metal surfaces facing each other), and can be bonded by applying sufficient mechanical pressure. The bondability of the Au–Au surfaces largely depends on the applied mechanical pressure and temperature [35]. The bonding is also a function of softening characteristic of the substrate. It is known that a soft-state material (which can act as a substrate) coated with gold can be bonded to metallic layers by using cold-welding at low-pressure [18–21]. Such soft-state substrate materials, however, are not adequate for application for large-scale inorganic devices due to their mechanical instability. On the other hand, PET film used in this study is thermoplastic, which means that it becomes pliable or moldable above a specific temperature and then solidifies upon cooling. These favorable characteristics of the PET film enabled low-pressure cold-welding between the two metal surfaces.

In this study, the low-pressure cold-welding process was carried out under a mechanical pressure of 0.4 MPa at 130 °C for 10 min. These conditions were carefully chosen considering the glass transition temperature (T_g) and the melting temperature (T_m) of the PET film [22,23] which are around 70 °C and 260 °C, respectively. This temperature ensures bonding between Au surfaces [34]. Prior to bonding, the bonding surfaces are irradiated under Ar plasma for 90 s to activate the surface also to eliminate any organic contaminants [37]. The plasma treatment is essential in low-temperature bonding to obtain improved bonding between surfaces. The elasticity and compliance of the soft-state PET film allows the gold surfaces to conform to one another owing to the increased gold-gold contact area and removal of loosely adsorbed contaminants [18]. It is noteworthy that the applied mechanical pressure is considerably lower (i.e. 1/250 times) compared to the one previously reported for a cold-welding method on a plastic substrate [8], and the pressure is within limits that are suitable for chip-size bonding [35,36]. Therefore, mechanical damages to the lifted-off film can be greatly reduced. After the low-pressure cold-welding process, the bonded sample on the PET film was immersed into a solution of HF:H_2O (1:10 v/v) for 12 h at room temperature, to separate the GaAs parent substrate by selective etching of AlAs sacrificial layer. After low-pressure cold-welding and the ELO process, an n-type metal grid (Au/Ge/Ni/Au) was formed on the thin-film GaAs solar cell by e-beam evaporation.

3. Result and discussion

To investigate the bonding quality, the GaAs substrate that had been bonded by the low-pressure cold-welding method was manually detached from the PET film. Fig. 2(a) shows a cross-sectional scanning electron microscope (SEM) image of the Au–Au bonding induced by low-pressure cold-welding on the GaAs substrate after detachment. The Au–Au bonding between the Cr/Au metallic layer on the PET film and the Pt/Au metallic layer on the GaAs substrate remained tight, leaving residual PET pieces (which were torn out of the host PET film) on the Au–Au bonding surface. The bonding test verified that the bonding between Au–Au surfaces is stronger than that between Au/Cr-PET substrate. In other words, the bonding strength between the GaAs substrate and PET film produced by low-pressure cold-welding was strong enough to hold the thin-film GaAs solar cell. By using this method, a thin-film GaAs solar cell was transferred onto the PET film after selective chemical etching of the AlAs sacrificial layer, as shown in Fig. 2(b). No visible cracking and/or peeled region and defects were found in

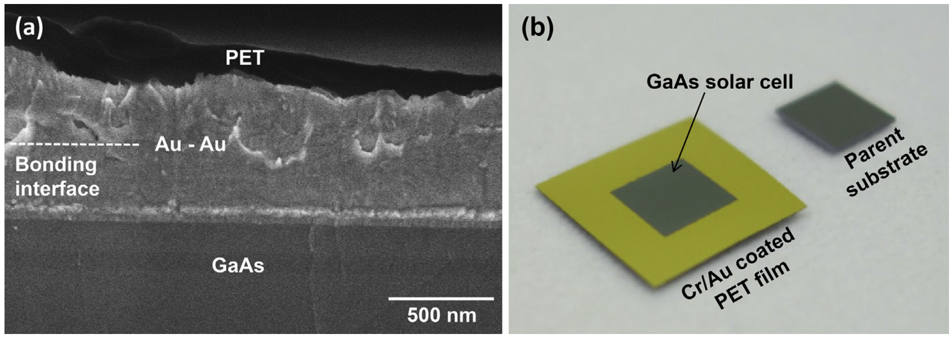

Fig. 2. (a) Cross section SEM image after detachment of the Au–Au bonded regions, and (b) Photograph of a lifted-off thin-film GaAs solar cell and the parent GaAs substrate.

the thin-film GaAs solar cell which can otherwise block the flow of photo-generated carriers. This was expected with the tightly bonded state produced by the low-pressure cold-welding process.

Fig. 3(a) plots the high-resolution X-ray diffraction (HRXRD) curves of both the as-grown GaAs solar cell, and the thin-film GaAs solar cell after the ELO process, showing a clear GaAs peak and its satellite peaks. Rather weak regularity of the HRXRD peaks of the thin-film GaAs solar cell is responsible for invisibly small surface wrinkles. The cusp next to the GaAs peak of the as-grown GaAs solar cell indicates a slightly compressive strained GaInP window. However, the cusp vanished after the ELO process due to the lattice relaxation during the lift-off process. Fig. 3(b) shows the normalized low-temperature (10 K) photoluminescence (PL) spectra of the as-grown GaAs solar cell and the thin-film GaAs solar cell after the ELO process. For the LT-PL measurement of active layer, the GaInP window layer was removed prior to measurement. A negligibly small spectral width broadening after the ELO process indicates the successful transfer and tight bonding of the brittle single crystalline thin-film GaAs solar cell onto the thermoplastic PET film using the low-pressure cold-welding method, without any significant damage or degradation of material quality. The PL peak position was blue-shifted from 831 nm to 821 nm during the ELO process which is due to the compressive strain present at the Au–Au bonding interface [24,25]. The welding temperature (~130 °C) used for the low-pressure cold-welding process is relatively low as compared with typical welding temperatures [15–17]. Note that the welding temperature is still above room temperature (RT). The coefficient of thermal expansion (CTE) of Au is twice larger than that of GaAs [26,27], and thus the GaAs thin-film solar cell is compressively strained after cooling down to RT after the low-pressure cold-welding process.

Fig. 4(a) shows the light current density-voltage (J–V) curves of the fabricated thin-film GaAs solar cell under 1-sun (AM1.5G, 100 mW/cm^2) illumination. The thin-film GaAs solar cell with an active area of 36 mm^2 had an open-circuit voltage (V_{oc}) of 1.04 V, short-circuit current density (J_{sc}) of 17.7 mA/cm^2, and a fill factor (FF) of 71.3%, resulting in a conversion efficiency of 13.2%. The metallic bonding layer that exists between the thin-film GaAs solar cell and the PET film determines the electrical properties of the thin-film GaAs solar cell. The metallic bonding layer performs not only as the rear contact electrode but also as back reflector, which increases the optical path length of the unabsorbed photons, thereby increasing photon absorption, which results in an increase of J_{sc}. The light trapping by the back reflector also affects photo-generated carrier concentration in the thin-film GaAs solar cell, leading to an increase of V_{oc} compared to equivalent GaAs substrate-based solar cells [29]. Furthermore, the large open-circuit voltage indicates a high material quality [30], which confirms that the thin-film GaAs solar cell has been successfully transferred onto the PET film by the low-pressure cold-welding method. It is known that a layer transferred at high-temperature can result in significant residual stress due to the combination of a large CTE difference and the excessively large temperature drop to RT [31,32]. Moreover, the bonding process performed under high-pressure can cause local

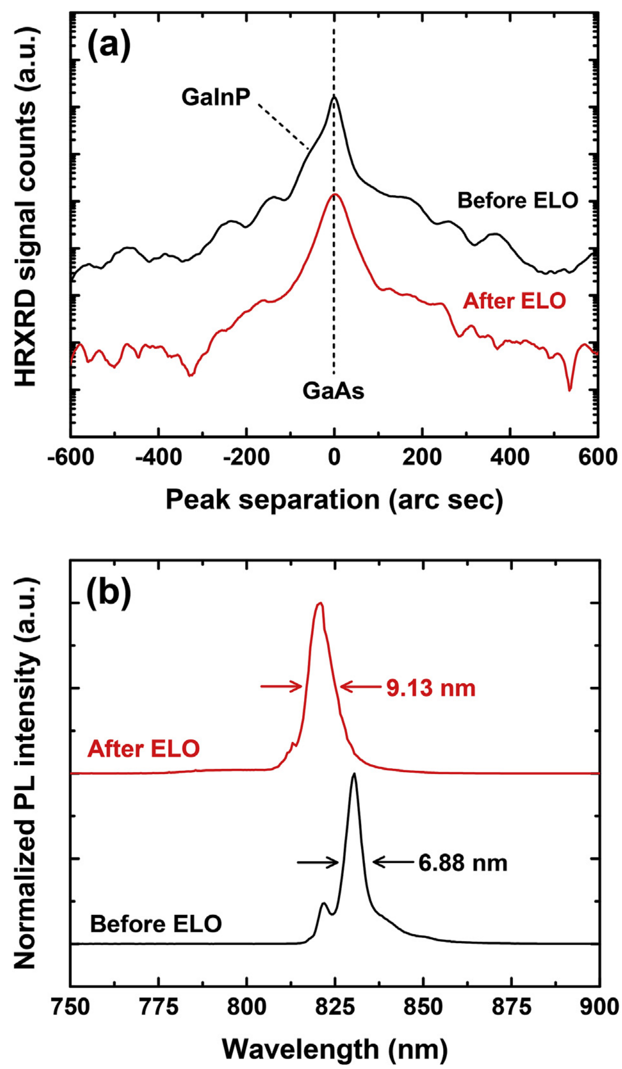

Fig. 3. (a) HRXRD diffraction curve of the as-grown GaAs solar cell and thin-film GaAs solar cell transferred onto PET film. (b) Normalized photoluminescence spectra of as-grown GaAs solar cell and thin-film GaAs solar cell after epitaxial lift-off (ELO) process at 10 K.

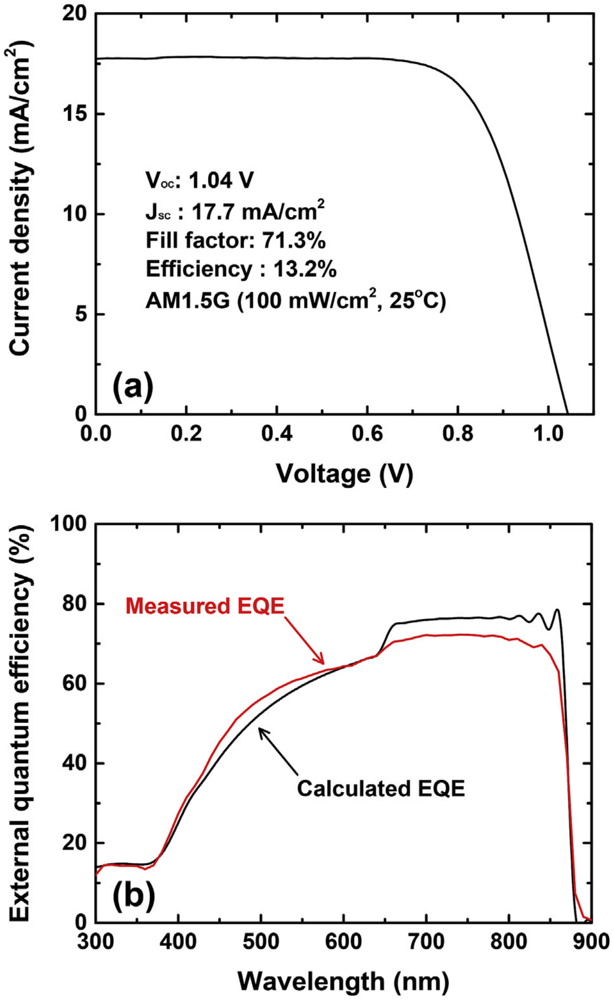

Fig. 4. (a) J–V curve of the thin-film GaAs solar cells (area: 0.36 mm^2) under AM1.5G 1-sun condition and (b) measured and calculated external quantum efficiency of the solar cell.

and/or global deformation of the plastic carrier substrate, resulting in significant variations in the thickness of the transferred semiconductor layer [33]. These drawbacks due to high-temperature and/or high-pressure employed during a conventional bonding process significantly increase the formation of defects and cracks, which can degrade the solar cell efficiency. However, by utilizing low-pressure cold-welding method, all these drawbacks were avoided. This is proven by Fig. 4(b) which shows the measured/calculated external quantum efficiency (EQE) spectra of the thin-film GaAs solar cell. As shown in the figure, the EQE spectrum of the fabricated thin-film GaAs solar cell is well matched to the calculated values. There are notable differences between the measured/calculated EQEs, in the wavelength range of 800–900 nm and beyond 650 nm. The oscillations shown by the calculated EQE using ray-tracing method in the spectral range of 800–900 nm is an artifact due to the resonant cavity effect occurring between BSF and window layer [28], and is not an indication of performance degradation. The difference between the measured/calculated EQEs in the range beyond 650 nm is worth discussing. The EQE spectrum is a figure-of-merit in evaluating the performance of active layers (GaAs base and emitter layers). However, the measured EQEs in Fig. 4(b) are not the ones obtained from the GaAs base/emitter layers only, but from GaInP window and BSF layers as well, whose role is to prevent surface recombination on the active layer surfaces. The presence of GaInP window and BSF layers result in additional light absorption in the fabricated device, which is one of the reason why the measured EQE is smaller than the calculated one in the range beyond 650 nm. The surface recombination on the GaInP window layer can also be held responsible for the smaller value of measured EQE compared to the calculated one. As shown in Fig. 1, the ELO process which releases the thin-film GaAs solar cell from the GaAs substrate is followed by the low-pressure cold-welding process. During this process, top-most GaInP window layer surface is exposed which has dangling bonds which leads to surface recombination of generated carriers. The surface recombination due to the GaInP window layer and resulting EQE degradation can be avoided by passivating the exposed surface with a dielectric layer. Forming a dielectric layer on the exposed surface after ELO process rather complicates the whole device fabrication process, and techniques to circumvent this issue are currently under investigation.

The thin-film GaAs solar cell transferred onto the PET film is flexible and thus can be integrated onto mechanically flexible modules and curved surfaces, for example, wavy building roof, helmets, and other uneven surfaces. To analyze the flexibility and mechanical stability, the fabricated thin-film GaAs solar cell was manually bent as shown in the inset of Fig. 5(a). Fig. 5(a) and (b)

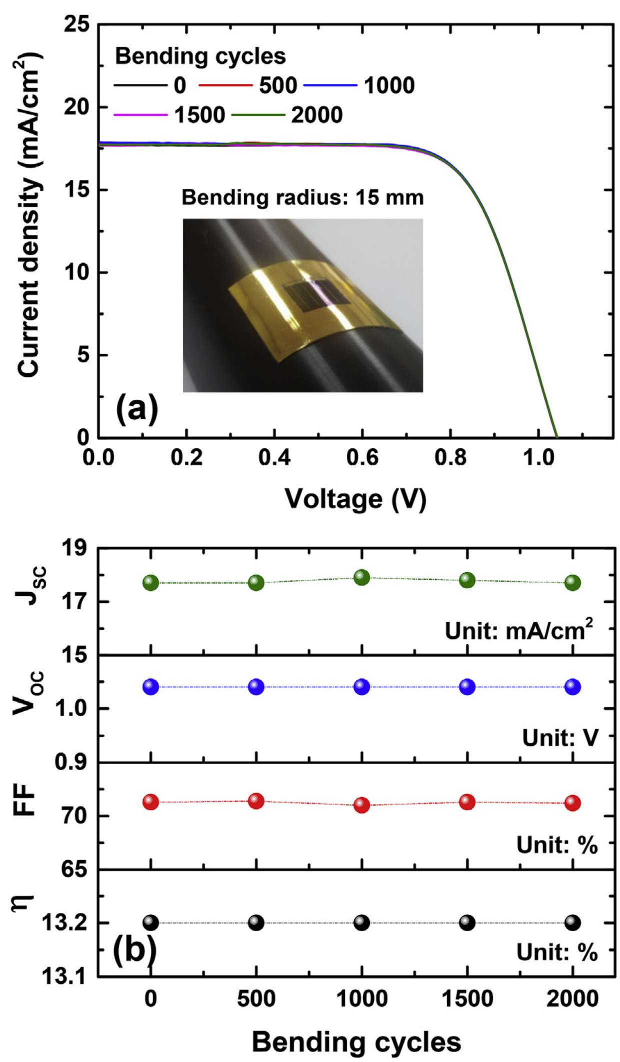

Fig. 5. (a) Performance of the flexible thin-film GaAs solar cell and (b) its detailed characteristics after bending test.

shows the J–V curve and detail characteristics of the thin-film GaAs solar cell, respectively, after multiple bending tests with a bending radius of 15 mm. The performance of the thin-film GaAs solar cell remained the same up to 2000 cycles of the bending, demonstrating its mechanical stability and robustness. It is notable that the weight of the fabricated thin-film GaAs solar cell was reduced by 1/27 by replacing the 350 μm-thick GaAs parent substrate, (weight density of 5.4 g/cm^3), with the 50 μm-thick PET film (weight density of 1.38 g/cm^3). In principle, the weight and production costs of flexible solar cells can be further reduced by transferring onto yet thinner and commercially available plastic substrates using the proposed method. By using the proposed method in this work, the fabricated solar cell showed a specific power (P_{sp}) of 1.501 kW/kg, which is rather higher than that of a GaAs solar cell transferred onto glass substrate [40] and that of a typical tandem solar cell [41]. The resulting flexible and light-weight thin-film GaAs solar cell has great potential for its use in various applications requiring flexibility and light weight along with high-efficiency.

4. Conclusion

We reported a new approach for realizing low-cost, light-weight and flexible thin-film GaAs solar cells based on low-pressure cold-welding and epitaxial lift-off. The proposed approach dramatically reduced the applied mechanical pressure by 1/125 compared to the method previously reported for cold-welding bonding, and prevented the mechanical damage caused to the transferred thin-film GaAs solar cell. The fabricated thin-film GaAs solar cell showed stable performance before and after 2000 cycles of bending test, performed under a bending radius of 15 mm, showing excellent flexibility, mechanical stability and robustness. The weight of the solar cell was remarkably reduced by replacing the heavy GaAs substrate with a light-weight plastic substrate. From these results, it is believed that this new bonding technique can be used for fabricating flexible inorganic semiconductor devices on plastic substrates, and can also be used for developing flexible and light-weight GaAs and InP based compound semiconductor devices such as light-emitting diodes, photodetectors, and other electronic/optoelectronic devices.

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